A Novel Approach of Fault Location in Electrical Transmission System using Smart Meters

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Received: September 2017 Revised: October 2017 Accepted: December 2017

ABSTRACT:
In the modern electrical grid, accuracy and speed of fault clearance are the major challenges which need to be addressed. This paper covers a case study of fault location techniques in electrical transmission network, using numeric relay and offline fault locator. Healthiness of electrical transmission line is ensured using line signature analyzer. Comparative study of online and offline fault location in electrical transmission network has been carried out and the inferences are drawn. On the basis data available it can be said that the frequency of occurrence of single line to ground fault is maximum (about 75%) among various types of faults. Data at 220 kV and 132 kV substations has been collected and analyzed, keeping focus on single line to ground fault. Architecture of Substation Automation System (SAS) using single communication technology based on IEC 61850-8 and IEC 61850-9 is explained. Proposed architecture consisting of numeric meter with Java Compilation Unit (JCU) and Ethernet switch standardized as per IEC 61850 is demonstrated. The Java source code to send indications to output port of numeric meter is included.

KEYWORDS*:* Single line to ground (1L-G) fault, Numeric relay, Line signature analyzer, Smart (Numeric) meter, Advanced metering infrastructure (AMI), Smart grid, Fault locator, International Electrotechnical Commission (IEC)-61850, Substation automation system (SAS), JCU.

1. INTRODUCTION

Distance protection proves to be more sensitive and highly selective as compared with overcurrent protection. It finds out the impedance at the faulty section of the transmission line from the measured value of voltages and currents at the relay location. The measured fault impedance is then compared with set value of the transmission line to be protected. If the fault impedance falls below the set value of the transmission line impedance, then it indicates that the fault is present between the relay location and the reach position [1]. Referring to Fig.1.when the fault occurs in the protected circuit, the relay connected to Current Transformer (C.T) and Potential Transformer (P.T) actuates and the relay contacts get closed. A D.C. current flows through the trip coil. As the trip coil of the Circuit Breaker (C.B) is energized, the C.B. contacts are opened. Based on the technological developments, there are three relay generations: electromagnetic, static and numeric. At every stage, there was an improvement in the relay practices. Numeric relay followed by a smart meter has become a key component of smart grid, Automatic Meter Reading (AMR), AMI and Supervisory Control and Data Acquisition (SCADA). As the relay is provided by processors, they are known as numeric relays. These relays can store the data. The working principle of numeric relay is based on sampling. The display parameters of a numeric relay are- Three voltages (V_r, V_y, V_b), three currents (I_r, I_y, I_b), kWh, kVAh, rkVAh (lead and lag), kVA Maximum Demand (kVA MD), number of resets, date and time, frequency and fault location [3].

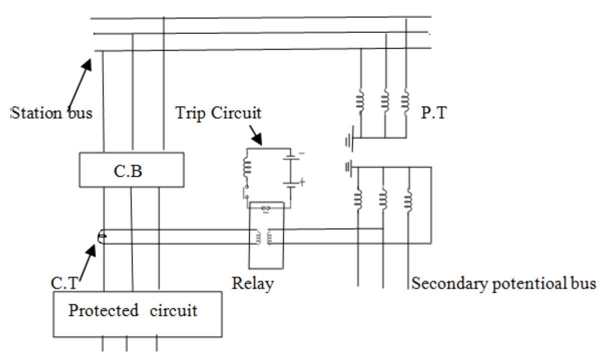

Fig.1. Basic connections of protective relay [2].

Trip circuit of the relay is explained through Fig.2.

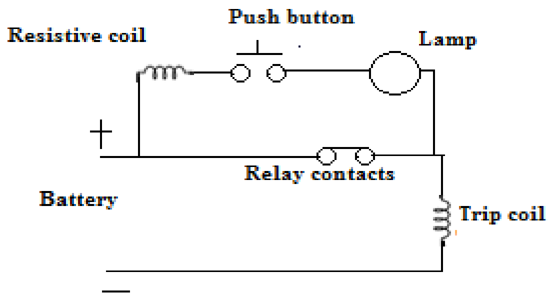

Fig.2. Trip circuit of the relay [2].

An extensive work has been done over the years for locating fault in electrical transmission and distribution network. Mainly fault location is based on travelling wave technique and impedance based technique [4]. Travelling wave method uses high frequency components of current and voltage; whereas, impedance based practice calculates line impedance as seen from the line terminals. Depending on single circuit or double circuit lines, fault location methods are categorized as single ended or double ended [5]. Fault distance estimation technique proposed by Aleena Swetapadma is based on Decision Tree Regression (DTR) technique [6]. Electromagnetic Time-Reversal (EMTR) based fault location method is demonstrated by Franc¸ ois Gaugaz [7]. Fault distance calculation proposed by R. Das is based on fundamental frequency component of voltage and current observed at the line terminal [8]. Impedance based fault location algorithm for ground faults in series capacitor compensated transmission lines is developed by Tirath Pal S. Bains. The work involves a novel double ended fault location algorithm for 1L–G fault and double phase to ground fault location [9]. The proposed method for fault location in DC distribution protection illustrated by Xianyong Feng covers the measurements of local voltage, current, and di/dt from a local protective device. The advantage of the system is that it does not require any communication for achieving coordination [10]. Adaptive system is the scheme which changes the operation of the algorithm data and/or structure in order to achieve an optimal state as external conditions change. Kulikov A.L., Obalin M.D., Vukolov V.U., Bezdushniy D.I. presented advantages of the developed adaptive algorithms on real electrical transmission lines [11]. In Real-Time Evaluation of Impedance-Based Fault Location Algorithms paper, three traditional impedance-based algorithms used for estimating the location of a fault on ac transmission lines are evaluated [12]. Synchrophasor based fault location algorithm for series-compensated transmission lines is demonstrated by Seyed Sina Mousavi Seyedi. Optimal estimator for series-compensated transmission lines fault location has been formulated in this paper. Proposed fault location method is independent of fault resistance and source impedance [13]. Trupti Hinge has presented a novice algorithm for fault detection, classification and location in smart grid using synchrophasor [14].

After paying the visits to different substations, data has been collected. This paper focuses on 1L-G Fault location and is organized as follows:

First the calculations for 1L-G Fault for the distance relay are introduced. This is followed by a technique for fault location using online and offline fault locator. Healthiness of the transmission line was understood by using line signature analyzer, and inferences are drawn. Proposed architecture of SAS by linking numeric meter with JCU using IEC 61850 is demonstrated. Finally, a comparison between fault location using numeric relay, fault locator, and numeric meter with JCU is illustrated.

2. DISTANCE RELAY 1L-G FAULT DATA

The distance relay under study is Alstom make, Micom P442.

A. Distance Relay zone calculations at 220kVAjinkyatara-Wankusawade, Maharashtra, India Substation.

The standard calculations for zones of protection viz. zone1, zone2, zone 3 and zone 4 are furnished below: [15]

Zone 1 reach = 80% of protected line i.e. 21.68 km.

Zone 2 reach = 50% of adjacent shortest line +100% protected line length i.e. 32.65 km.

Zone 3 reach = 100% of protected line +100% of longest line length i.e. 38.2 km.

Ratio of secondary to primary Impedance = CT Ratio/PT Ratio = 0.400

For total line length:

$|Z_1| = 4.3907 \angle 79.33$

$|Z_0| = 14.095 \angle 76.434$

Where, zero sequence (Z_0) and positive sequence (Z_1) impedances are calculated for total line length.

Arc resistance = R_{arc} = 5.00 Ω

Tower footing resistance = R_{tower} = 15Ω

Total Resistance in secondary = 8 Ω

Positive sequence reactance = X_1

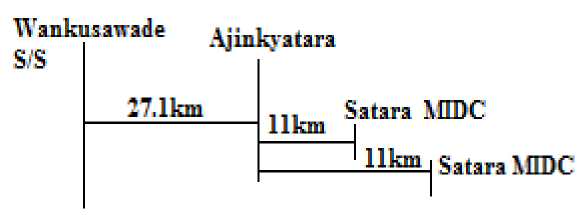

Fig.3. Wankusawade – Ajinkyatara Line.

B. Distance Relay zone calculations for Single Line to Ground Fault:

Zone 1

Line to ground reactance = XG_1 = (80% of protected line length) * X_1 * CT Ratio/PT Ratio) = 3.45

Line to ground resistance= (R_{1line} + R_{arc} + R_{tower}) * CT Ratio/PT Ratio = 8.652

Zone 2

Line to ground reactance = XG_2= (100% Protected line + 50% shortest adjacent line) * X_1 * CT Ratio/PT Ratio = 5.198

Line to ground resistance= RG_2 = ($R_{2\ line}$ + R_{arc} + R_{tower}) * CT Ratio/PT Ratio=8.98

Zone 3:

Line to ground reactance = XG_3= (2 km line length) * X_1 * CT Ratio/PT Ratio = 0.32

Line to ground resistance = RG_3= (2 km line + R_{arc} + R_{tower}) * CT Ratio/PT Ratio= 8.06

Zone 4:

Line to ground reactance = XG_4 = (100% of protected line + 100% of longest line) * X_1 * CT Ratio/PT Ratio = 6.08

Line to ground resistance = RG_4 = (R_{1line} + R_{arc} + R_{tower}) * CT Ratio/PT Ratio = 9.149

C. *Zone Calculations of Distance Relay for Ratnagiri Wind Power Project (RWPPL)–Miraj line*

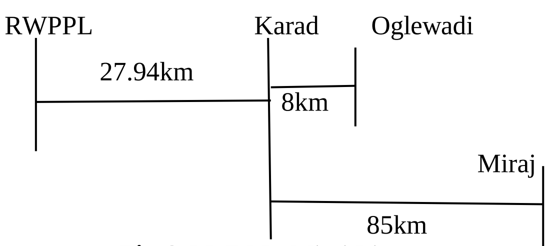

Fig.4. RWPPL–Miraj Line.

CT Ratio =800/1A
PT Ratio=220000/110V
Protected line parameters (from reference chart) [15]:
$Z_1 = 0.0752 + j0.4140 = 0.421 \angle 79.67$
$Z_0 = 0.3093 + j1.205 = 1.244 \angle 75.58$

Conductor size 0.4 T
Zone 1 reach= 80% of protected line
Zone 2 reach= 50% of adjacent shortest line i.e. 31.94 km
Zone 3 reach=100% of adjacent longest line i.e. 112.94km
Zone 4 reach=10% of protected line length i.e. 2.79km
Ratio of secondary to primary impedance = CT Ratio/PT Ratio=0.400

D. *Micom P442 Relay outputs for 1L-G Fault*

1 L-G fault on phase A is represented as shown in Fig. 5.

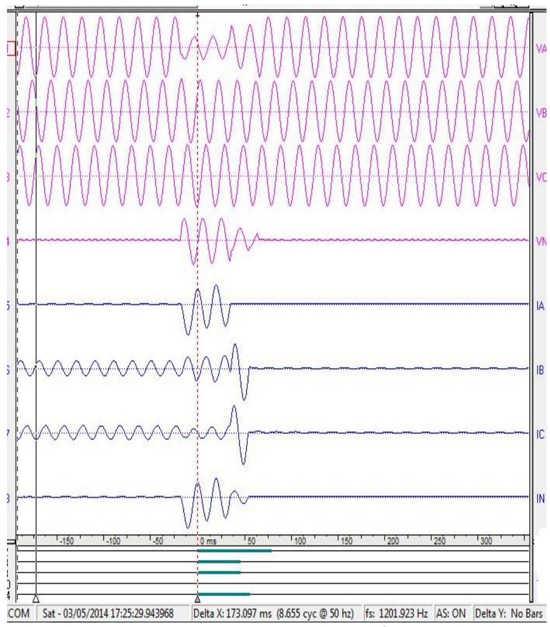

Fig. 5. Micom P442 relay outputs for 1L-G Fault.

Table 1. Line Data [16].

Details of protected line	
Length of protected line	27.94 km
Positive sequence resistance per km	0.0752 Ω
Positive sequence reactance per km	0.414 Ω
Positive sequence impedance per km	0.421 Ω
Zero sequence resistance per km	0.309 Ω
Zero sequence reactance per km	1.205 Ω
Zero sequence impedance per km	1.244 Ω
Mutual resistance per km	0.000 Ω
Mutual reactance per km	0.000 Ω
Positive sequence resistance for protected line	2.101 Ω
Positive sequence reactance for protected line	11.567 Ω
Positive sequence impedance for protected line	4.703 Ω
Positive sequence Impedance angle	79.673degree
Zero sequence resistance for protected line	8.633 Ω
Zero sequence reactance for protected line	33.668 Ω
Zero sequence impedance for protected line	34.757 Ω
Zero sequence impedance angle	75.587 Ω

Table 2. Details of adjacent shortest line.

Length of the adjacent shortest line	8.000 km
Positive sequence resistance of adjacent. line per km	0.0752 Ω
Positive sequence reactance of adjacent line per km	0.405 Ω
Positive sequence impedance of adjacent line per km	0.412 Ω
Positive sequence resistance for protected line	0.602 Ω
Positive sequence reactance for protected line	3.240 Ω
Positive sequence impedance for protected line	1.318 Ω
Positive sequence impedance angle	79.449 degree

Table 3. Details of adjacent longest line.

Length of the adjacent shortest line	85.000 km
Positive sequence resistance of adjacent line per km	0.0752 Ω
Positive sequence reactance of adjacent line per km	0.398 Ω
Positive sequence impedance of adjacent line per km	0.405 Ω
Positive sequence resistance for protected line	6.392 Ω
Positive sequence reactance for protected line	33.830 Ω
Positive sequence impedance for protected line	13.771 Ω
Positive sequence impedance angle	79.268 degree

TABLE 4. CT and PT Details.

CT Primary	800A
CT Secondary	1A
PT Primary	220kV
PT Secondary	110kV
CT/PT Ratio	0.4

E. ***Resistive reach settings:***

Primary full load current is considered as 800 A.

Resistance at this current
= (0.8*(PT Primary*10^3)/1.732) / (2*Primary full load current) = 63.510

Load resistance in secondary
= Resistance at this current*(CT /PT Ratio) - R_L= 25.404

Arc resistance in case of phase to phase fault = (80% of R_L) = 20.323Ω

Tower footing resistance in case of phase to ground fault (90% of R_L = 22.864 Ω)

Where, R_{L} is the total line resistance.

F. ***Power swing setting***

ΔR =10 to 30% of arc resistance in case of phase to phase fault = 4.065 Ω

ΔX= 10 to 30% of arc resistance in case of phase to phase fault = 4.065Ω

3. FAULT LOCATOR FOR OVERHEAD TRANSMISSION LINE

Working principle of fault locator [17]:

Fault locators are classified as:

- Online fault locator
- Offline fault locator

Online system requires the power system parameters. Data during the fault event is taken into the account. On the other hand, offline fault location is based on Multiple Pulse Eco Co-Relation Technique and need not require any system parameters for fault location [18]. A high frequency (1.5 kHz) coded pulse of 5kV, is injected across the line and the ground. It is generated by the signal generator which is inbuilt in the kit. The kit operates on the principle that, when the fault occurs, the line impedance falls down. The signal sent across the line and the ground returns back from the point of occurrence of fault. The fault location will be the function of the time taken for the signal to come back to the starting point. The information related to the type of fault and location is decoded. The report is generated using TADMA software through which a complete view of the line can be observed.

A. Functions of Line Signature Analyzer:

- Virtual line patrolling.
- Verification of transmission line length.
- Ensuring the healthiness of the line.
- Restoration of the line as early as possible to guarantee the reliability of power supply.

B. ***Understanding the healthiness of transmission line using Line Signature Analyzer:***

Healthiness of 132kV Lonand – Satara road line (Maharashtra, India) was checked by using line signature analyzer.

C. Steps performed while conducting the test:

The conductor type used is 0.2 AAAC (All Aluminium Alloy Conductors). Coupling capacitors were bypassed at both the ends; and then supply was switched on. Then, two sets of readings were taken by opening and closing earth switch alternately at remote end (Satara road line). Finally, complete analysis of data was retrieved through the laptop loaded with TADMA software. While closing the test, after switching off the equipment, all the three phases were earthed. The hook rod connections were removed from the line and discharged the hook rod connections from the line.

D. *Report Analysis*

The length of the phase B of Lonand – Satara road line indicated in the report, retrieved using TADMA software is 35.9 km. It indicates the normal condition of the phase B, because it is the actual length of the Lonand – Satara road line. It was observed that, the line length found out by using line signature analyzer is more than the actual one when the wave trap is connected into the circuit.

4. FAULT LOCATION IN ELECTRICAL TRANSMISSION SYSTEM USING SMART METER

Smart meter is the most significant device in Intelligent Electronic Devices (IED) family. The smart meter available in the market does not display the fault location. The proposed work includes the demonstration of fault distance, date and time of the fault occurrence on the numeric meter.

A. IEC 61850:

International Electrotechnical Commission (IEC) 61850 is the standard introduced in SAS applications. It is a standard, which describes the data modeling and communication protocol. It is entirely different than Transmission Control Protocol (TCP)/Internet Protocol (IP). Intelligent Electronic Devices (IEDs) are incorporated in SAS for controlling, protection, and monitoring purpose. IEC 61850 allows real time messages to ensure reliability of the power system. Communication services in IEC 61850 architecture is described in Fig.6. Electrical Network Monitoring and Control System (ENMCS) is connected to IEDS through a station bus. GOOSE signals are used for critical messages like load shedding or intertrip [19]. ENMCS and IEDs communicate with each other via Manufacturing Message Specification (MMS) service. This service has no time requirement and it is based on TCP/IP communication layer [19]. IEC 61850 allows exchange of real time messages over the communication network.

Numeric relay along with communication feature is a key component of SAS. Reliability of the system is dependent on the integrity and interoperability of the components of the system. IEC 61850 was developed by focusing on the improvement in the interoperability of the equipments [20]. This paper describes SAS using IEC 61850.

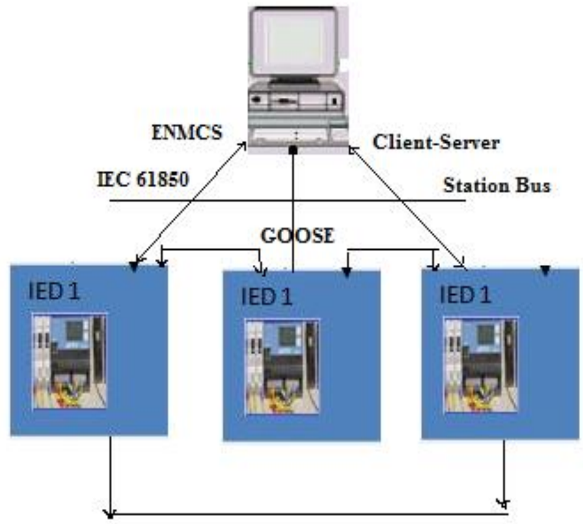

Fig. 6. Communication in IEC 61850 architecture [19].

B. Substation Automation System Architecture [20]

Architecture with conventional switchgear and CT/PT are connected with copper wire as shown in Fig.7, with advancement in communication, this conventional wiring can be minimized using IEC 61850.

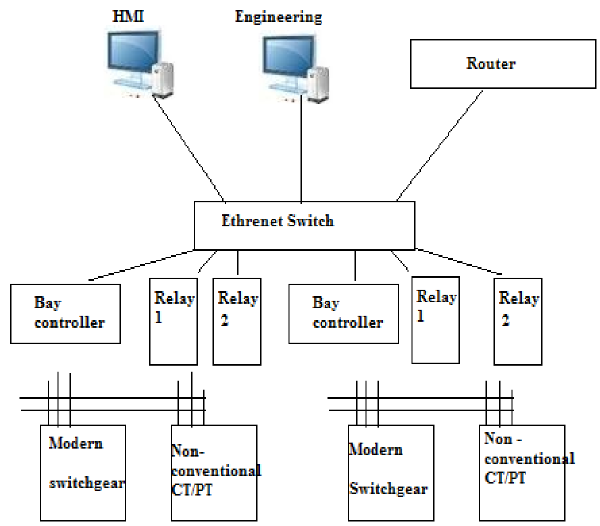

Fig.7. Architecture with conventional copper wiring

Use of an Ethernet switch between bay level and process level leads to reduction in hard copper wiring as shown in Fig. 8.

IEC 61850 uses same communication technology for process bus and substation bus.

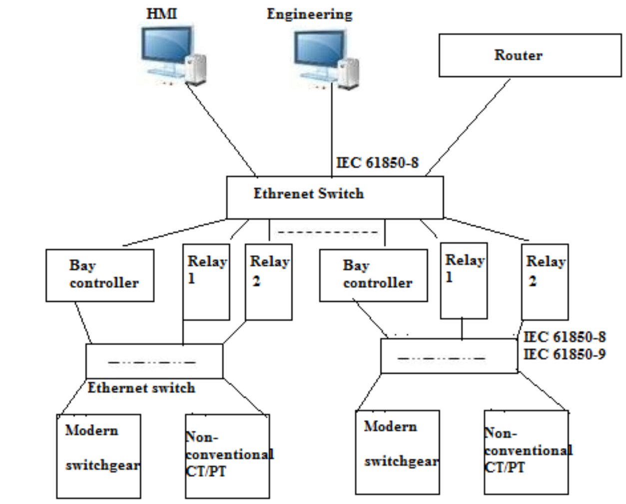

Fig.8. Communication network for station bus using IEC 61850-8 and for process bus using IEC 61850-8 and IEC 61850-9 [20].

The above Fig. 8 can be reduced to a single communication technology by using IEC 61850-8 and IEC 61850-9 which is shown in Fig.9.

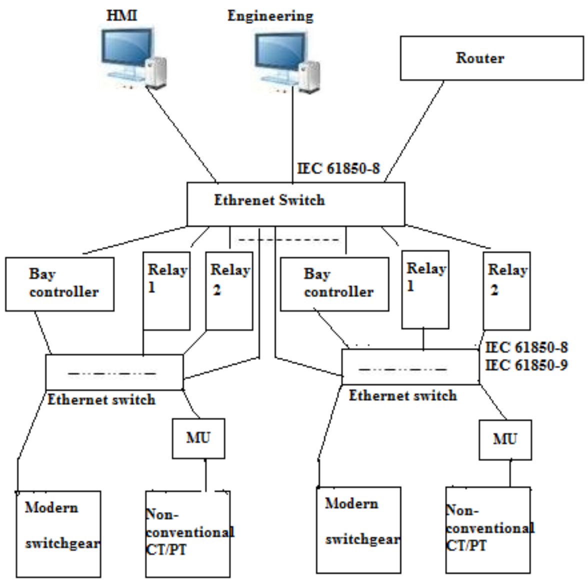

Fig.9. Architecture using single communication technology using IEC 61850-8 and IEC 61850-9 [20].

C. Merging unit (MU)

Instrument transformers on each phase will require separate IEDs, and it will lead to a complicated network; which can be reduced by using merging unit. Merging unit is at process level. It connects CTs and PTs to relays and bay controller in bay level.

The output of instrument transformers from the three phases is merged in this unit. Outputs from CTs and PTs are standardized as per IEC 61850. These instrument transformers can be conventional or nonconventional.

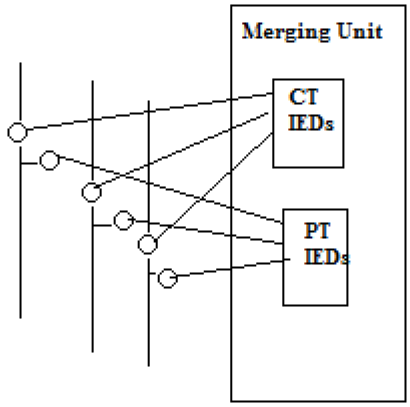

Fig.10. Connections of merging unit with CTs and PTs.

The connection between MU in process level and bay level is standardized as per IEC 61850. In IEC 61850, service requests are exchanged using Ethernet. The services are prioritized based on the criticality of the fault event. IEC 61850 GOOSE messages carry high-critical protection commands which should be delivered as early as possible. GOOSE operates with publisher approach by using multicast messages [21]. Multicasting means, a message is sent from one transmitter to many receivers at a time. The IED sending GOOSE message publishes the message on a Local Area Network (LAN). All remaining IEDs connected to LAN will receive the message. But few of them can subscribe the message [21].

D. Proposed Architecture

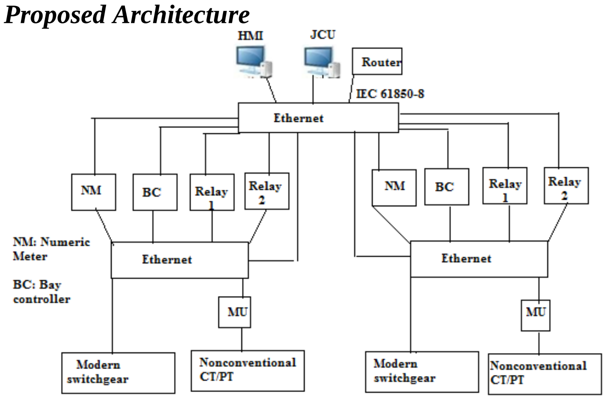

Fig.11. Proposed architecture with numeric meter connected to JCU through Ethernet switch standardized as per IEC 61850.

The analogue output from instrument transformers in MU is sampled and then converted to digital signals which are fed to JCU as shown in Fig.12. Under healthy condition i.e. $V_r = V_y = V_b$, and $I_r = I_y = I_b$, JCU is in sleep mode. Whereas, under fault condition, $V_r \neq V_y \neq V_b$, and $I_r \neq I_y \neq I_b$, JCU is in active mode.

At the time of disturbance, the numeric meter will display an additional parameter, which is length of the fault point from the bus.

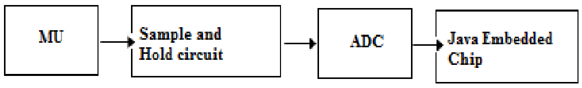

Fig.12. MU linked with Java Embedded Chip (JEC)

The Java source code to send indications to output port of numeric meter is given below:

```
// Write to output port
import java.io.*;
importjava.util.*;
importjavax.comm.*;
public class DataWrite {
static Enumeration portList;
staticCommPortIdentifierportId;
static String messageString = Fault data\n";
staticSerialPortserialPort;
staticOutputStreamoutputStream;
public static void main(String[] args) {
portList = CommPortIdentifier.getPortIdentifiers();
while (portList.hasMoreElements()) {
portId = (CommPortIdentifier) portList.nextElement();
if (portId.getPortType() ==
CommPortIdentifier.PORT_SERIAL) {
if (portId.getName().equals("COM1")) {
            //if (portId.getName().equals("/dev/term/a"))
{
try {
serialPort = (SerialPort)
portId.open("faultdata", 2000);
                } catch (PortInUseException e) {}
try {
outputStream = serialPort.getOutputStream();
                } catch (IOException e) {}
try {
serialPort.setSerialPortParams(9600,
                      SerialPort.DATABITS_8,
                      SerialPort.STOPBITS_1,
SerialPort.PARITY_NONE);
                } catch
(UnsupportedCommOperationException e) {}
try {
outputStream.write(messageString.getBytes());
                } catch (IOException e) {}
            }
          }}}}
```

A numeric meter monitors three phase voltages and currents [22]. It will perform following operations:

- Data collection from instrument transformers
- Sampling of these analogue values
- Filtering the measured signals
- Determination of type and location of the fault
- Display of the results

5. CONCLUSION

A case study has been carried out for 1L-G fault location by using numeric distance relay. The drawbacks of numeric distance relay are:

1. The zone impedance settings of the relay are carried out manually. This may lead to an error.
2. Relay maloperates in case of CT saturation and higher order harmonics.

Healthiness of the electrical transmission line has been checked using line signature analyzer and it was observed that, the distance measured by line signature analyzer cannot be accurate because, it measures the length of the jumper connecting the wave trap in addition to the actual fault distance.

Shortfalls of line signature analyzer and fault locator are:

1. The line signature analyzer and fault locator unit is bulky and costly.
2. Online fault locator cannot be used for spur transmission lines.
3. Open circuit faults cannot be located using online fault locator.

Proposed novel advancement in locating 1L-G Fault in electrical transmission network using smart meter connected to JCU involves display of additional parameters of the numeric meter which is fault distance. Future scope of the work would be an intimation of the fault distance on smart phone by establishing persistent socket connection.

6. ACKNOWLEDGMENT

Authors are thankful to Jain University, Bangalore for providing required research facilities and encouragement.

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